U.S. DEPARTMENT OF COMMERCE
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PB-299 206

Survey of Solidification/Stabilization Technology for Hazardous Industrial Wastes

(U.S.) Army Engineer Waterways Experiment Station, Vicksburg, MS

Prepared for

Municipal Environmental Research Lab, Cincinnati, OH

Jul 79

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati, OH 45268

Research and Development

PB 299206

EPA

Survey of Solidification/ Stabilization Technology for Hazardous Industrial Wastes

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TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/2-79-056	2.	3. RECIPIENT'S ACCESSION NO. PB299206
4. TITLE AND SUBTITLE Survey of Solidification/Stabilization Technology for Hazardous Industrial Wastes		5. REPORT DATE July 1979 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Environmental Laboratory		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Engineer Waterways Experiment Station Vicksburg, Mississippi 39180		10. PROGRAM ELEMENT NO. 1DC818, SOS 1, Task 27 11. CONTRACT/GRANT NO. IAG-D4-0569
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Interim 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Robert E. Landreth 513/684-7871

16. ABSTRACT

Stabilization/solidification or fixation is a process for treating industrial solid wastes (primarily sludges) that contain hazardous constituents to prevent dissolution and loss of toxic materials into the environment. Most of these treatment processes are designed to produce a monolithic solid of low permeability. Some of the stabilization/solidification processes can further control the loss of toxic materials by (a) reacting chemically with the toxic constituents to produce new inert solid compounds that bind the potential pollutants into stable crystal lattices; (b) controlling the pH and redox potential so that toxic compounds are maintained under conditions where the materials have minimum solubility; (c) covering the solid waste material with a coating that does not react with the waste, but prevents water from reaching the material. Prevent solidification/stabilization systems are grouped into seven classes of processes. The advantages and disadvantages of each approach is discussed. Abstracts from technical information furnished by companies developing or marketing solidification/stabilization processes or marketing equipment specifically for these processes are presented.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Stabilization, leaching, sludge, wastes	Solid Waste Management Chemical Stabilization (Fixation)	13B

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED 20. SECURITY CLASS *(This page)* UNCLASSIFIED	21. NO. OF PAGES 50 22. PRICE A03-A01

EPA Form 2220-1 (Rev. 4-77)

* U.S. GOVERNMENT PRINTING OFFICE: 1979-657-060/5347

EPA-600/2-79-056
July 1979

SURVEY OF SOLIDIFICATION/STABILIZATION TECHNOLOGY FOR HAZARDOUS INDUSTRIAL WASTES

by

Environmental Laboratory
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi 39180

Interagency Agreement No. EPA-IAG-D4-0569

Project Officer

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report presents a summary of treatment techniques that may be of use in the solidification and/or chemical stabilization of industrial sludges containing hazardous materials. The report explores one possible option which testing techniques may demonstrate can be used in containing hazardous wastes. This report is issued for information purposes only and should not be interpreted as an endorsement of or recommendation for the use of these processes.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Stabilization/solidification or fixation is a process for treating industrial solid wastes (primarily sludges) that contain hazardous constituents to prevent dissolution and loss of toxic materials into the environment. Most of these treatment processes are designed to produce a monolithic solid of low permeability. Some of the stabilization/solidification processes can further control the loss of toxic materials by (a) reacting chemically with the toxic constituents to produce new inert solid compounds that bind the potential pollutants into stable crystal lattices; (b) controlling the pH and redox potential so that toxic compounds are maintained under conditions where the materials have minimum solubility; (c) covering the solid waste material with a coating that does not react with the waste, but prevents water from reaching the material.

Present solidification/stabilization systems can be grouped into seven classes of processes.

a) Solidification through cement addition.

b) Solidification through the addition of lime or other pozzolanic materials.

c) Techniques involving embedding wastes in thermoplastic materials such as bitumen, paraffin or polyethylene.

d) Solidification by addition of an organic polymer.

e) Encapsulation of wastes in a inert coating.

f) Treatment of the wastes to produce a cementitious product without major additions of other constituents.

g) Formation of a glass by fusion of wastes with silica.

The advantages and disadvantages of each approach is discussed. Abstracts from technical information furnished by companies developing or marketing solidification/stabilization processes or marketing equipment specifically for these processes are presented.

This report was submitted in partial fulfillment of Interagency Agreement No. EPA-IAG-D4-0569 by the U.S. Army Engineer Waterways Experiment Station under the sponsorship of the U.S. Environmental Protection Agency. This report covers work performed from June 1976 to December 1978.

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ACKNOWLEDGEMENTS

This technology survey was conducted by the Environmental Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under sponsorship of the Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency.

The authors are Dr. Philip G. Malone and Dr. Larry W. Jones. Mr. Douglas W. Thompson reviewed the manuscript and provided valuable criticism. The abstracts presented in the Appendix are available due to the efforts of the many companies that responded to inquiries and submitted technical information for inclusion in this survey. The project was conducted under the general supervision of Dr. John Harrison, Chief, Environmental Laboratory, Mr. Andrew J. Green, Chief, Environmental Engineering Division, and Mr. Norman R. Francingues, Jr., Chief, Treatment Process Research Branch.

The guidance and support of Mr. Robert E. Landreth, Mr. Norbert B. Schomaker and the Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency are gratefully acknowledged. The diligent and patient efforts of Ms. Rosie Lott and Ms. Maureen Smart, typists, are also gratefully acknowledged. The Director of WES during the course of this work was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

SECTION 1

INTRODUCTION

BACKGROUND

Hazardous wastes have only recently been adequately described and given the attention they warrant and a great deal remains to be learned about their management and disposal. Hazardous wastes have been defined by the Environmental Protection Agency (1) as wastes, or combinations of wastes, that pose a substantial present or potential hazard to human health or living organisms because: (a) such wastes are non-degradable or persistent in nature, (b) they can be biologically magnified, (c) they are noxious or toxic, or (d) they may cause, or tend to cause, detrimental cumulative effects.

In the last few years Federal and state legislation has been directed toward insuring proper treatment, control and disposal of hazardous industrial wastes. Emphasis has been placed upon the overall design of environmentally sound waste disposal systems; random and uncontrolled dumping of raw wastes is no longer an acceptable practice. Industry must concern itself with all aspects of disposal practices including soil and geologic features of the disposal site, runoff and groundwater contamination, bioaccumulation or biodegradation, and reclamation and/or final disposition of the site. The largest step in this direction is Public Law 94-580--The Resource Conservation and Recovery Act of 1976, which amends the earlier Solid Waste Disposal Act to provide for a wide range of activities such as a hazardous waste regulatory program, a call for the elimination of open dumping, and grants to certain communities to improve their solid waste management systems.

The traditional idea that hazardous wastes can be simply dumped or diluted has given way to the realization that all wastes ultimately are returned to the environment. There is a finite limit on the ability of the environment to absorbed waste materials and remain unaltered. Large expenditures of money and manpower are being made to develop methods for the proper treatment and/or containment of noxious and toxic wastes. Several responses to the problem are being actively pursued under private and governmental auspices. Deep, abandoned mines which occur in stable geologic formations are being investigated as repositories for hazardous wastes such as long-lived radioactive materials (2) or even for such wastes as flue gas cleaning sludges (3). Continued controlled dumping in the deep ocean is also being considered for many of the less noxious wastes (4). Isolating landfills with impervious liners or landfilling noxious materials in sealed containers is currently practiced in several special purpose landfills (5). This report is concerned with another alternative; that of chemically fixing or structurally isolating the hazardous materials in a solid, crystalline, or polymeric matrix so that

the resulting monolithic solid mass can be safely handled, transported and disposed of using established methods of landfilling or burial.

Waste fixation is for the most part synonomous with stabilization/solidification. Chemical fixation and stabilization/solidification are general terms used to designate processes that can be used to immobilize, isolate, or contain industrial waste materials, especially semi-solids or sludges. Fixation usually has as one of its goals the production of a solid material from a semi-liquid waste. The terms solidification or stabilization are usually used interchangably although they represent different ideas.

Solidification suggests the production of a solid, monolithic mass with sufficient structural integrity to be transported in some conveniently-sized pieces without requiring any secondary containers. The solidification aspect of fixation comes from a Department of Transportation (DOT) regulation that all liquid radioactive waste material be converted into solid form (by absorption on solids, drying, etc.) prior to transportation in interstate routes. Some fixation technology has as its goal only the solidification of wastes to comply with this DOT regulation.

Stabilization suggests immobilization of toxic substances by reacting them chemically to form insoluble compounds or perhaps entrapping the toxic element or compound in a watertight, inert polymer or stable crystal lattice. The dissolution of wastes has always been a major problem in containing a toxic material so, much of the emphasis in stabilization has been placed in preventing the waste from coming in contact with water or creating pH and oxidation-reduction conditions that minimize the solubility of the toxic compounds in the waste. Many fixation systems combine these two ideas by producing an impermeable mass that isolates the wastes from any surrounding water (soil-water or groundwater) and at the same time holds the chemical conditions (pH and Eh) of any water that does enter the solidified wastes in the region of minimum solubility for the toxic compounds in the wastes (6).

Major Types of Toxic Industrial Wastes

In any discussion of toxic industrial wastes, the major categories that appear are (a) flue-gas cleaning sludges, (b) waste streams containing toxic organic materials, (c) waste streams containing toxic inorganic materials.

Flue gas cleaning (FGC) sludges are produced in scrubbing operations designed to remove sulfur oxides and other pollutants from flue gas at power generating or metal extraction facilities. The sludges produced are usually a thixotropic mass of microcrystals of calcium sulfite and calcium sulfate with some flyash and are extremely difficult to dewater. Water which comes in contact with the sludge, or which leaches through it, typically acquires a high calcium content (500-700 mg/ℓ) and a high sulfate content (1200-1500 mg/ℓ). This sulfate level is well above the acceptable limits for potable water. Depending upon the coal source or ore being processed relatively high levels of many heavy metals are contained in, and easily leached from the FGC sludge (3).

By the end of this decade, flue gas scrubbers will produce 30 to 60 million tons of this sludge annually. Because of the large volume and unique character of FGC sludges, a technology devoted exclusively to their solidification/stabilization or fixation is rapidly developing (7). Portions of this report will deal with waste fixation techniques tailored specifically for use with FGC sludges. In some cases, fixation methods for FGC sludges are adaptable to other, oftentimes more toxic sludges.

Many toxic organic wastes are used solvents or oils or organic-rich sludges that collect in storage facilities for solvents or fuels. In some circumstances much of this waste can be reclaimed. Where reclaiming is not economical, the material must be disposed of by land application, incineration or burial. Unfortunately, most solidification/stabilization techniques have not been successful in containing organics. Organics especially oily materials interfere with the polymerization of silicate materials so the cement or pozzolan-based fixatives tend to loose cohesion and never produce a "set". Fixing techniques that depend on encapsulation with organic resins encounter problems due to the solvent effects of the organic wastes. Any fixation techniques that require that the waste be heated (as in asphalt or plastic encapsulation procedures) often cannot be used with organic-rich wastes because of vaporization or danger of fire.

Many companies involved with waste stabilization refuse to accept organic-rich wastes for stabilization. Other operators will accept only limited amounts of organics and will mix the organic waste with large volumes of dried inorganic material that will serve as an absorbant. While theoretically it is possible to demonstrate that many toxic organics, especially chlorinated organics, are tightly absorbed to solid phases such as clay or char, there is not a great deal of interest in attempting to stabilize these wastes. The ash from organic wastes or sludge is a much more easily stabilized material than an unincinerated organic sludge.

REQUIREMENTS OF TOXIC WASTE TREATMENT

The ideal fixative renders the toxic contaminants chemically nonreactive and immobile so that no secondary containment is necessary. For example, incorporation into a stable crystal lattice would effectively isolate the toxic material from any environmental interactions. Maintaining the pH in the range of 9 to 11 immobilizes the majority of multivalent cations as insoluble hydroxides. Sludges with high concentrations of particular cations could be treated with fixatives chosen specifically to immobilize these contaminants. Anions, although typically much less toxic, are much more difficult to bind into an unleachable product. Chlorides and sulfates, the most common anionic sludge components, produce only a few insoluble salts. To contain anions such as these, the waste must be physically isolated from any leaching medium.

To be completely effective, the waste treatment must produce a final mixture which has physical properties such that its disposal does not permanently render the land unsuitable for alternate uses. However, the production of treated wastes with soil-like character which might be suitable for agricultural use seems highly unlikely in cases where the major contaminants

are multivalent cations and/or high levels of salts. The action of organic acids normally produced by the biological activity in agricultural soils would be expected eventually to mobilize even the most tightly bound contaminants. Such mobilized constituents would then be taken into the food chain or washed into the groundwater. The most secure final form of treated waste is an monolithic mass which has good dimensional stability, freeze-thaw resistance, low permeability, a high bearing capacity, and resistance to attack by biological agents. An end product such as this could be used as a foundation for buildings or roads, or simply buried and covered over in a landfill.

The ideal fixing process, does not require extensive heat-treatment nor large amounts of energy-intensive reactants. Also, the sludge materials should be reclaimable by some reasonable technique as some of the sludge contaminants (for example, manganese and chromium) are predicted to be in a critical supply in the future.

SCOPE OF THIS REPORT

This report is a compilation of available state-of-the-art techniques, processes and systems for solidification and/or stabilization of hazardous industrial wastes. Section 2 includes a brief description of the categories of fixed materials and a compilation of their relative advantages and disadvantages. This is followed in the appendix by an alphabetical list of companies that solidify or fix hazardous industrial wastes or sell fixation materials or equipment. A very brief description of each company's fixing process, the wastes which they can and cannot stabilize, the approximate costs of the process, and the past experience of the company is included. All material in this report is taken from product literature, publicly-circulated, technical reports and correspondence with vendor companies. The data and product claims are presented as submitted by the vendor companies. All costs figures are only rough estimates which depend upon many broad assumptions. Costs, where given, are only for approximate comparison between fixation processes, and do not represent quotations for specific applications. For further details the reader is encouraged to correspond directly with the companies.

This compilation includes responses to questionnaires submitted to all companies known to be active in the area of hazardous industrial waste fixation or stabilization. No endorsement of companies included is intended or implied. Companies not appearing on this list were simply not known to the authors or did not respond to inquiries.

SECTION 2

FIXATION TECHNOLOGY

There exist a large number of fixation methods which are now available or are under development, all having as their goal the safe, ultimate disposal of hazardous wastes. Ultimate disposal implies the final disposition of persistent, nondegradable cumulative and/or harmful wastes. Three primary goals of fixation of hazardous waste for ultimate disposal generally are: (a) to improve the handling and physical characteristics of the waste, (b) decrease the surface area across which transfer and loss of contained pollutants can occur, and (c) limit the solubility of any pollutants contained in the waste. These goals can be met in a variety of ways, but not all techniques attempt to meet all three goals. Thus, individual fixation techniques may solve one particular set of problems but be completely unsatisfactory for others.

The important attributes, advantages and disadvantages of the following major categories of industrial waste fixation systems are discussed:

a) Cement-based techniques.

b) Lime-based techniques.

c) Thermoplastic techniques (including bitumen, paraffin and polyethylene).

d) Organic polymer techniques.

e) Encapsulation techniques.

f) Self-cementing techniques.

g) Glassification.

Since these waste fixation systems vary widely in their applicability, cost and pretreatment requirements, many are limited as to the types of waste that can be economically processed. Selection of any particular technique for waste fixation must include careful consideration of the containment required, the cost of processing, the increase in bulk of material and the changes in handling characteristics. The design and location of any landfill that will eventually receive the fixed waste is also a major consideration in deciding on the degree of containment and the physical properties which will be required.

CEMENT-BASED TECHNIQUES

Cement-based waste fixation techniques owe much of their development to the use of this system in disposal of low-level radioactive waste (8). The cement-waste radioactive products have been ruled as acceptable for permanent disposal by both U. S. agencies and the International Atomic Energy Agency (9).

Common cement or "portland cement" is produced by firing a charge of limestone and clay or other silicates mixtures at a high temperature. The resulting clinker is ground to a fine powder to produce a cement that consists of about 50% tricalcium and 25% dicalcium silicates (also present are about 10% tricalcium aluminate and 10% calcium aluminoferrite). The "cementation" process is brought about by the addition of water to the anhydrous cement powder. This first produces a colloidal calcium-silicate-hydrate gel of indefinite composition and structure. Hardening of the cement is a lengthy process brought about by the interlacing of thin, densely-packed, silicate fibrils growing from the individual cement particles. This fibrilliar matrix incorporates the added aggregates and/or wastes into a monolithic, rock-like mass. The success of the hardening process is affected by compounds such as sulfates, borates, salts of some metals, and a variety of organic compounds. Five types of portland cements are generally recognized based upon variations in their chemical composition and physical properties (10):

a) Type I is the "normal" cement of the building trade as described above and constitutes over 90% of the cement manufactured in the USA.

b) Type II is used in the presence of moderate sulfate concentrations (150-1500 mg/kg).

c) Type III has a high early strength and is used where a rapid set is required.

d) Type IV develops a low heat of hydration and is used in large mass concrete work.

e) Type V is a special low-alumina, sulfate-resistant cement used with high sulfate concentrations (>1500 mg/kg).

The types which have been used for waste fixation are Type I and to a much lesser extent Types II and V.

Most hazardous wastes slurried in water can be mixed directly with the cement and suspended solids will be incorporated into the rigid matrix of the hardened concrete. This procedure is especially effective for wastes with high levels of toxic metals since at the pH of the cement mixture most multivalent cations are converted to insoluble hydroxides or carbonates. Metal ions may also be taken into the crystal structure of the cement minerals that form. Materials in the waste such as sulfides, asbestos, latex, and solid plastic wastes may actually increase the strength and stability of the waste concrete. However, the presence of certain inorganic compounds in the hazardous waste and the mixing waters can be deleterious to the setting and curing of the waste-concrete mix (10). Impurities such as organic materials, silt,

clay, coal or lignite may delay setting and curing of common portland cement for as long as several days. All insoluble materials passing through a No. 200 sieve (<74 micron particle size) are undesirable as they may be present as dust or may coat the larger particulates weakening the bond between the particles and the cement. Salts of manganese, tin, zinc, copper and lead may cause large variations in setting time and significant reductions in physical strength--salts of zinc, copper and lead being the most detrimental. Other compounds which are especially active as retarders of the setting of portland cement include sodium salts of arsenate, borate, phosphate, iodate, sulfide--even at concentrations as low as a few tenths of a percent of the weight of the cement used. Products containing large amounts of sulfate (such as flue gas cleaning sludges) not only retard the setting of concrete but, by reacting to form calcium sulfoaluminate hydrate cause swelling and spalling in the solidified waste-concrete. The special low alumina (Type V) cement was developed for use in circumstances where high sulfate is encountered to prevent this reaction.

A number of additives have been developed for use with cement to improve the physical characteristics and decrease the leaching losses from the resulting fixed sludge. Many of the additives used in waste fixation are proprietary and cannot be discussed here; but experimental work on the fixation of radioactive waste has shown some improvement in cement-based fixation and retention of nuclear waste by adding clay or vermiculite as absorbents (6). Sodium silicate has reportedly been used to bind contaminants in cement fixation processes, but this additive causes an increase in volume to occur during the setting of the cement-waste mixture (9).

Recent testing done by Brookhaven National Laboratory under the sponsorship of the Nuclear Regulatory Commission indicates that a mixture of sodium silicate and Type II portland cement produced by a rapid set with no retardation from metallic ions (11). This sodium silicate appeared to precipitate most interfering ions in a gelatinous mass and so to remove interferences and speed setting. Of radwastes tested only boric acid wastes produced any inhibition of set in the cement mixture. The development of a gel is important in the setting of the cement-waste-silicate mixture. Excessive mixing after the gel forms seems to cause slower setting and lessen final strength.

Brookhaven National Laboratory developed a polymer-impregnation process that can be used to decrease the permeability of concrete-sludge mixtures (9). The pores of the waste-concrete are filled by soaking in styrene monomer. The soaked material is then heated to bring about polymerization. This process results in significant increase in the strength and durability of the concrete-waste mixture. Surface coatings on concrete-waste composites have been examined extensively. The major problems encountered have been poor adhesion of the coating to the waste or lack of strength in the concrete material containing the waste. Surface coating materials that have been investigated include asphalt, asphalt emulsion, and vinyl (12). No surface coating system for cement-based fixed material (waste-concrete) is currently being advertised.

Advantages of the cement-based fixing systems are:

a) Raw materials are plentiful and inexpensive.

b) The technology and management of cement mixing and handling is well known; and the equipment is commonplace. Specialized labor is not required.

c) Extensive drying or dewatering of waste is not required because cement mixtures require water and the amount of cement added can be adapted to wide range of water contents.

d) The system is very "tolerant" of chemical variation. The natural alkalinity of the cement used can neutralize acids. Cement is not effected by strong oxidizers such as nitrates or chlorates. Pretreatment is required only for materials that retard the setting reactions of cement.

e) Leaching characteristics can be improved where necessary by coating the resulting product with sealant.

f) Variation in the amount of cement used can produce very high bearing capacities making the waste concrete good sub-grade and sub-foundation material.

Disadvantages of cement-based systems are:

a) Relatively large amounts of cement are required for most fixing processes. However this may, in part, be off-set by the low cost of material. The weight and volume of the final product is normally about double that of other solidification processes.

b) Uncoated cement-based products may require a well-designed landfill for burial. Experience in radioactive waste disposal indicates that some wastes are leached from concrete, especially by mildly acidic leaching solutions.

c) Extensive pretreatment, or higher cost cement types or additives may be necessary for wastes containing large amounts of impurities which effect the setting and curing of the waste-concrete (such as borates and sulfates).

d) The alkalinity of cement drives off ammonium ion as ammonia gas.

e) Cement is an energy-intensive material.

LIME-BASED TECHNIQUES

Waste fixation techniques based on lime-products usually depend on the reaction of lime with a fine-grained siliceous (pozzolanic) material and water to produce a concrete-like material (sometimes referred to as a pozzolanic concrete). The most common pozzolanic-type materials used in waste treatment are flyash, ground blast-furnace slag or cement-kiln dust. All of these materials are themselves waste products with little or no commercial value. The use of these waste products to consolidate another waste is often an advantage to the processor who can treat two waste streams at the same time.

For example, the production of a pozzolanic reaction with power plant flyash permits the flue gas cleaning sludge to be combined with the normal flyash output and lime (along with other additives) to produce an easily-handled solid.

Advantages of lime-based techniques which produce pozzolan cements are several:

a) The materials are often very low in costs and widely available.

b) Little specialized equipment is required for processing as lime is a common additive (to neutralize wastes) in other streams.

c) The chemistry of lime-pozzolanic reactions is relatively well-known.

d) Extensive dewatering is not necessary because water is required in the setting reaction.

The lime-based systems have many of the same potential disadvantages as cement-based techniques:

a) Lime and other additives add to the weight and bulk to be transported and/or landfilled.

b) Uncoated lime-fixed materials may require specially designed landfills to guarantee that the material does not lose potential pollutants by leaching.

THERMOPLASTIC TECHNIQUES (INCLUDING BITUMEN, PARAFFIN AND POLYETHYLENE)

Development of the use of thermoplastic fixation systems in radioactive waste disposal has led to a waste containment system that can be adapted to industrial wastes. In processing radioactive waste with bitumen, or other thermoplastic material, the waste is dried, heated and dispersed through a heated plastic matrix. The mixture is then cooled to solidify the mass, and is usually buried in a secondary containment system such as a steel drum. Variations of this fixation system can use other thermoplastic organic materials such as paraffin or polyethylene.

The process requires some specialized equipment to heat and mix the waste and plastic matrix, but equipment for mixing and extruding waste-plastic is available. The ratio of matrix to waste is generally quite high 1:1 to 1:2 fixative to waste (on a dry weight basis). The matrix and the dry waste must be mixed at temperatures ranging from 130°C to 230°C depending on the melting characteristics of the material and type of equipment used.

A variant of this process uses an emulsified bitumen product which is miscible with the wet sludge. With this process the mixing can be done at any convenient temperature below the boiling point of the mixture. The overall mass must still be heated and dried before it is suitable for disposal. Ratios of emulsion to waste of 1:1 to 1:1.5 are necessary for adequate incorporation (9).

In many cases, the types of waste disposed rule out the use of any organic-based fixation technique. Organic chemicals that are solvents for the matrix obviously cannot be used directly in this disposal system. Strongly oxidizing salts, such as nitrates, chlorates, or perchlorates, will react with organic matrix materials and cause slow deterioration. At the elevated temperatures necessary for processing the matrix-oxidizer mixtures are extremely flammable. Leach testing undertaken on anhydrous salts embedded in bitumen as a matrix indicates that rehydration of the embedded compound can occur when the sample is soaked in water and can cause the asphalt or bitumen to split apart, greatly increasing the surface area and the rate of waste loss (11). Some salts (such as sodium sulfate) will naturally dehydrate at the temperatures required to make the bitumen plastic; so these easily dehydrated compounds must be avoided in thermoplastic stabilization.

The major advantages of the thermoplastic-based disposal systems are:

a) The leach loss rates are significantly lower than those observed with cement-based systems.

b) By disposing of the wastes in a dry condition, the overall volume of the waste is greatly reduced.

c) Most matrix materials are very resistant to attack by aqueous solutions. Microbial degradation is minimal.

d) Most matrices adhere well to incorporated materials.

e) Materials embedded in a thermoplastic matrix can be reclaimed if needed.

The principal disadvantages of thermoplastic-based disposal systems are that:

a) Expensive, complicated equipment requiring highly specialized labor is necessary for processing.

b) These systems cannot be used with materials that decompose at high temperatures, especially citrates and certain types of plastics.

c) There is a risk of fire in working with organic materials such as bitumen at elevated temperatures.

d) During heating, some mixes can release objectionable oils and odors causing secondary air pollution.

e) The waste material to be incorporated must be dried which requires large amounts of energy. Incorporating wet wastes greatly increases losses through leaching.

f) The incorporation of tetraborates or iron and aluminum salts in bitumen matrices causes premature hardening and can clog and damage mixing equipment.

g) Strong oxidizers usually cannot be incorporated into organic materials without oxidizing reactions occurring. High concentrations of strong oxidizers at elevated processing temperatures can cause fires.

h) Dehydrated salts incorporated in a thermoplastic matrix will slowly rehydrate if the mixture is soaked in water. The rehydrated salt will expand the mixture and cause the waste block to fragment.

i) The plasticity of matrix-waste mixtures may require that containers be provided for transportation and disposal of the material.

ORGANIC POLYMER TECHNIQUES

Organic polymer techniques were developed as a response to the requirement for solidification of radioactive waste for transportation. The most thoroughly tested organic polymer solidification technique is the urea-formaldehyde (UF) system. The polymer is generally formed in a batch process where the wet or dry wastes are blended with a prepolymer in a waste receptacle (steel drum) or in a specially designed mixer. When these two components are thoroughly mixed, a catalyst is added and mixing is continued until the catalyst is thoroughly dispersed. Mixing is terminated before the polymer has formed and the resin-waste mixture is transferred to a waste container if necessary. The polymerized material does not chemically combine with the waste; it forms a spongy mass that traps the solid particles. Any liquid associated with the waste will remain after polymerization. The polymer mass must often be dried before disposal.

Several organic polymer systems are available that are not based on urea-formaldehyde resin. Dow Industrial Division is developing vinyl ester-styrene polymer systems (Nuclear Binder 101) for use with radioactive waste (13). Testing of this material is currently underway in the Nuclear Regulatory Commission's research programs.

The Polymeric Materials Section at Washington State University has developed a polyester resin system that is being used in solidification of radioactive wastes. This system is currently in a pilot-plant stage in the processing of radwastes (14, 15).

The major advantages of the organic polymer systems (especially the UF-resin system) are:

a) Less fixative is required for solidifying the same amount of waste. The waste-to-fixative ratio is usually about 30% greater for a UF organic polymer system than with cement.

b) The waste material treated is usually dewatered, but not necessarily dried. The finished, solidified polymer, however, must be dried before ultimate disposal.

c) The organic resin used is consistently less dense (specific gravity is approximately 1.3) than cement. The low density reduces the transportation costs related to the fixative and fixed product.

d) The solidified resin is non-flammable and high temperatures are not required for forming the resin.

The major disadvantages of the organic resin technique, especially the urea-formaldehyde resin system, are:

a) No chemical reactions occur in the solidification system that chemically bind the potential pollutants. The particles of waste material are trapped in an organic resin matrix.

b) Catalysts used in the UF systems are strongly acidic and the waste-UF mixture must be maintained at pH 1.5 $\pm$ 0.5 for solidification to occur in a rapid manner. The low pH can put many waste materials into solution. If the pH is not lowered to 1.5, the polymerization is slow; solids will settle out, and the fixed material will not be trapped effectively.

c) Uncombined or "weep" water is often associated with polymerized waste. This must be allowed to evaporate to produce a fully-cured polymer. The "weep water" may be strongly acid and may contain high levels of pollutants. Waste-UF mixtures shrink as they age and will produce "weep water" during aging.

d) Some catalysts used in polymerization are highly corrosive and require special mixing equipment and container liners.

e) The reactions producing the resin, may release fumes that can be harmful or disagreeable even in low concentrations.

f) Some cured resins are biodegradable (especially UF-based systems) according to several manufacturers.

g) Secondary containment in steel drums is common practice in organic resin-waste fixation. This raises costs in processing and transportation.

ENCAPSULATION TECHNIQUES

All fixation systems depend on binding particles of waste material together. To the extent to which the binder coats the waste particles, the wastes are encapsulated. The systems addressed under encapsulation are those in which waste that has been bonded together is inclosed in a coating or jacket of inert material. A number of systems for coating solidified industrial wastes have been examined by TRW Corporation (12). In most cases coated materials have suffered from lack of adhesion between coatings and bound wastes and lack of long-term integrity in the coating materials. After investigating many alternative binding and coating systems, TRW Corporation produced detailed plans for what it considered the optimum encapsulation system. The TRW-developed system has been thoroughly tested and published data on the process are available (16).

The TRW encapsulation system requires that the waste material be thoroughly dried. The dried wastes are stirred into a acetone solution of modified 1,2 polybutadiene for five minutes. The mixture is allowed to set for two hours. The optimum amount of binder is 3% to 4% of the fixed material on a dry weight basis. The coated material is placed in a mold, subjected to slight mechanical pressure, and heated to between 120°C (250°F) and 200°C (400°F) to produce fusion. The agglomerated material is a hard, tough, solid block. A 3.5 mm (1/4 in.)-thick polyethylene jacket is fused over the solid block and adheres to the polybutadiene binder. In a 360 kg to 450 kg (800-1000 lbs) block the polyethylene would amount to 4% of the fused waste on a weight basis.

The major advantage of an encapsulation process is that the waste material never comes in contact with water, so very soluble materials, such as sodium chloride, can be successfully encapsulated. The impervious jacket eliminates all leaching into contacting water as long as the jacket remains intact.

The major disadvantages of encapsulation are:

a) The resins required for encapsulating are expensive.

b) The process requires large expenditures of energy in drying, fusing the binder, and forming the jacket.

c) Polyethylene is combustible with a flash point of 250°C making fires a hazard.

d) The system requires extensive capital investments in equipment.

e) Skilled labor is required to operate molding and fusing equipment.

SELF-CEMENTING TECHNIQUES

Some industrial wastes such as the flue gas cleaning or desulfurization sludges contain large amounts of calcium sulfate or calcium sulfite. A technology has been developed to treat these types of wastes so that they become self-cementing (17). Usually a small portion (8-10% by weight) of the dewatered waste sulfite/sulfate sludge is calcined under carefully controlled conditions to produce a partially dehydrated cementitious calcium sulfate or sulfite. This calcined waste is then reintroduced into the waste sludge along with proprietary additives. Flyash is added to adjust moisture content. The finished product is a hard, plaster-like material with good handling characteristics and low permeability.

The major advantages of self-cementing systems are:

a) No major additives have to be manufactured and shipped to the processing site.

b) The process is reported to produce faster setting times and more rapid curing than comparable lime-based systems.

c) The material produced is stable, non-flammable and non-biodegradable.

d) There are reports of effective heavy metal retention perhaps related to chemical bonding of potential pollutants (17).

e) These systems do not require completely dry waste. The hydration reaction uses up water.

The major disadvantages of the self-cementing systems are:

a) Only high sulfate or high sulfite sludges can be used.

b) Self-cemented sludges have much the same leaching characteristics as cement and lime-based systems.

c) Additional energy is required to produce the calcined cementitious material.

d) The process requires skilled labor and expensive machinery in calcining waste and mixing the calcined waste with additives to produce the fixed waste.

GLASSIFICATION

Where material is extremely dangerous or radioactive, it is possible to combine the waste with silica and fuse the mixture into glass (18). Glasses are only very slowly leached by naturally-occurring water, so this approach is generally assumed to produce a safe, material for disposal without secondary containment.

The major advantages of glassification are:

a) The process is assumed to produce a high degree of containment of wastes.

b) The additives used are relatively inexpensive (syenite and lime).

The major disadvantages of glassification are:

a) The process is energy-intensive. A charge must be heated to 1350^{o}C to produce a satisfactory melt.

b) Some constituents especially metals may be vaporized before they combine with the molten silica in the glass.

c) Specialized equipment and trained personnel are required for this type of operation.

From the discussion of fixation techniques given above, it can be seen that a wide variety of possible fixation systems exist and obviously not every system is applicable to every waste in every situation. The amount and character of the material to be stabilized, the economics involved and the

properties of the disposal site all work into a decision on fixation procedures to be used. By careful evaluation of economics, the hazardous nature of the material and the containment provided by geologic and hydrologic situations at surrounding landfills it should be possible to work out a minimum cost for responsible disposal of a particular waste.

The cost for waste fixation processes are geared to the volume of the waste to be fixed; therefore, it may become cost-advantageous to concentrate hazardous waste materials into a minimum volume to reduce handling and additive requirements. When hazardous wastes are concentrated the precautions involved in handling and transportation are necessarily increased so on-site stabilization (or at least solidification) would be desirable. In fact, solidification (stabilization) may simply become a unit operation to complete the waste treatment system and the waste treatment operations could be tailored to produce the hazardous residue in a minimum volume with a pH and chemical composition that is compatible with the stabilization system that is required to insure safe containment under specified landfill conditions.

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APPENDIX

SOURCES OF FIXATION TECHNOLOGY

Organizations included in this appendix are those that develop and/or market solidification/stabilization techniques or manufacture equipment for solidification/stabilization processes. Many of these companies hold one or more significant patents in the waste treatment industry. This listing is not all inclusive; many chemical landfills have fixation operations that are used only on material to be landfilled on that site. These operations are usually tailored only to the waste arriving at that site and stabilized specifically for conditions at that landfill. If the stabilization operation is not clearly defined and is not marketed off the landfill site; no attempt was made to include the service in this list.

The information given here was obtained from answers to questionnaires submitted to the companies involved and from company literature made available to the authors. Data obtained from the companies with regard to strength or leach testing of fixed material were reproduced without critical examination. An attempt was made to present all estimates of physical properties in comparable metric units.

The authors have abstracted the data obtained from each vendor. Any negotiations for the use of any particular service or process will no doubt require more information and testing or evaluation of fixed material produced from the client organization's waste. The physical properties and leach test results given here may not be obtainable with every waste.

a. Name of Vendor: Atcor Washington Inc.
Division of Chem Nuclear Systems, Inc.
Park Mall
Peekskill, NY 10566

Contact: M. Brownstein, Director
(914) 739-9000

b. Category of fixing process: The process is classed as a masonry-based solidification systems (using cement).

c. Types of wastes treated: System is primarily designed to effectively solidify typical wastes from both boiling water reactor and pressurized water reactor nuclear power plants (which include 25% Na_2SO_4, 12% H_2BO_3, bead type ion exchange resin and various filter media - solka floc, diatomaccous earth and filter aid). The Atcor Radwaste Solidification System includes an in-line mixer/feeder which fills any size container, permits inclusion of bulky items and flushes clean with a minimum of water. All operation procedures are remote and/or automatic.

d. Types of waste excluded from treatment: Sludges which do not combine with cement could not be handled, however, testing for specific sludges is required to ensure application suitability.

e. Cost of fixation: Cost is variable depending upon waste to be treated. Dry masonry cement is added up to a volume equal to the volume of waste which gives final product about 130% of volume of original waste. Cement cost is approximately 9 cents per kilogram, but capital expenditure, transportation and personnel costs will vary greatly with the individual job.

f. Leach and strength tests: Leach and strength studies showing product acceptability for cement-based radwaste systems are numerous. The product is a monolithic cement structure exhibiting no free water and an acceptable leach rate for shallow-land burial.

g. Examples of past applications and current contracts: At present the Atcor system is used solely within the commercial nuclear power industry, however, studies are currently under way to use system for solidifying arsenic wastes and incinerator-generated wastes. Radwaste solidification systems have been purchased by 11 major power companies including: Northern States Power Company (Monticello and Prairie Island), Wisconsin Public Service Co. (Kewanee), Wisconsin Electric and Power Co. (Point Beach), Tennessee Valley Authority (Bellefonte), Taiwan Power Co. (Chin-Shan and Kuoseng), Duquesne Light Co. (Beaver Valley), and others.

a. Name of Vendor: Chemfix, Inc.
1675 Airline Highway
Kenner, LA
(504) 729-4561
or mail correspondence to:
P. O. Box 1572
Kenner, LA 70063

Contact: J. M. Calloway
Executive Vice-President

/or Bentley B. Mackay, Jr.
President

b. Category of fixing process: Inorganic chemical additives (cements and soluble silicates) are mixed with the wastes to produce a gelling reaction that is followed by hardening. A mobile treatment plant that can handle up to 380,000 liters/10 hour shift is provided. The additives consist of up to 10% by volume of the waste. The process varies with the percent solids and nature of the wastes. Generally the higher the percent solids the lower the additive requirement.

c. Types of wastes treated: Most types of waste can be accepted for this processing. The additives react with polyvalent metal ions producing stable, insoluble, inorganic compounds. Nonreactive materials are physically entrapped in the matrix structure resulting from the reaction process. Process is usually custom designed for each type of wastes.

d. Types of waste excluded from treatment: Wastes containing certain organic compounds, toxic anions and non-toxic but undesirable constituents are not treated. In many cases specified pretreatment will allow solidification/stabilization systems to be used.

e. Approximate cost of processing: Varies greatly with the % solids and nature of the waste. (Laboratory testing to determine cost is provided.)

f. Data on leach and strength tests: Extensive leach tests have been run on a variety of "processed" material and are available from the company. Data available includes results of cyclic leach tests, saturation extraction tests and non-equilibrium extraction systems. Acceptable leaching results have been obtained from a variety of industrial wastes from automotive manufacturing, electronic fabrication and other operations. The strength of fixed material varies with the amounts of additives used. The fixed material can vary from a soil-like mass to a solid (concrete-like) monolith with high bearing capacity.

g. Examples of past applications and current contracts: The "CHEMFIX" process has been applied to the following wastes: chemical and allied products (160×10^6 liters), petroleum refining (105×10^6 liters), transportation equipment (88×10^6 liters), primary metals (18×10^6 liters), municipal waste water treatment, flue gas desulfurization wastes, dredging spoils, and radioactive wastes.

"CHEMFIX" is a registered trademark of Chemfix, Inc.

a. Name of Vendor: Dravo Lime Company
650 Smithfield Street
Pittsburgh, PA 15222

Contact: C. J. McCormick
(412) 566-4444

b. Category of fixing process: Dravo Lime Company's solidification additive, Calcilox, is a dry, free flowing, light grey-colored powder of inorganic origin. It is hydraulically active and when added to the slurry improves its handling and ultimate land disposal characteristics by imparting structural integrity to the settled slurry. The process could probably best be classed as pozzolanic or cementitious.

c. Type of waste treated: Calcilox is applicable to all calcium-based SO_X scrubber waste as typically produced from coal-fired utility scrubbers. Calcilox is also applied to many inorganic mineral processing tailings that contain a large percentage of silica and alumina. Typical applications are on fine coal preparation wastes and uranium mill tailings.

d. Type of waste excluded from treatment: Sludges containing organics and sewage wastes cannot be treated.

e. Approximate cost of processing: The weight percent of Calcilox additive dosages range from 5 to 15% of the dry slurry solids weight. Low dosages (5-10%) are used with mechanically dewatered wastes (55 to 70% solids) and higher dosages (10-15%) with lower solids slurries such as thickener underflows with 25 to 35% solids. Costs are site and process dependent: no firm estimates are available.

f. Data on leach and strength tests: Leach data are available from field tests on flue gas cleaning wastes and indicate reduced leach rates when compared to raw sludges. Typically, leaching rates are reduced one to two orders of magnitude below untreated wastes. The strength of the product is controlled by the mixing ratios, but the product has a dry, clay-like consistency similar to compacted clayish soil.

g. Examples of past application and current contracts: Extensive experience has been gained through contracts with several large power plants such as the Bruce Mansfield Power Station in Shippingport, PA, the Duquesne Light Company Phillips Power Station, and Allegheny Power Service Company's Pleasants Station. Current coal waste applications are at several large American Electric Power Company mines and at smaller independent operations in Ohio and West Virginia. Ongoing tests are being conducted with several uranium producers in the western United States under a Department of Energy contract.

"Calcilox" is a registered trademark of Dravo Lime Co.

a. Name of Vendor: Environmental Technology Corporation
Suite 200
1517 Woodruff Street
Pittsburgh, PA 15220

Contact: Albert R. Kupiec, Vice-President
(412) 431-8586

b. Category of fixing process: The ETC Solidification System requires commonly available reagents in addition to the lime which is currently used in wastewater processes. The hazardous wastes are neutralized and solidified resulting in a sludge which totally encapsulates the moisture and chemically binds heavy metals and other chemicals within the sludge.

Lime is required to neutralize the acidity of the hazardous waste and to complex most of the heavy metal cations as insoluble hydroxides. Chemistry of the reagents is well known, but before now they had not been used in a single system. One of the reagents acts as an ion exchange media for complete heavy metal removal and removes excess water within the system. The other reagents act as binders which bridge the sludge particles and increases the physical strength and load-bearing capacity of the final sludge. The final sludge produced is soil-like in appearance.

c. Types of waste treated: The hazardous wastes involved in the development of the ETC system are mostly spent pickling acids from steel mills. Sulphuric acid composes the largest amount of wastes by volume. Other types of wastes treated include (1) hydrochloric acids; (2) other pickling acids; (3) spent plating solutions; (4) sludge from industrial waste treatment plants; (5) scrubber sludges; and (6) organic sludges.

d. Types of waste excluded from treatment: None listed.

e. Approximate cost of processing: Cost of neutralizing and solidification of waste pickle liquors varies with the method of mixing and type of lime used. Treatment with dry lime followed by ETC reagents costs 1.00 cents per liter. Addition of lime as a slurry increases the amount of the other reagents required so that the costs rise. Other sludges can be stabilized at costs of 0.40 cents to 3.00 cents per liter.

f. Data on leach and strength tests: Leach tests were conducted in the open in lined, V-shaped trenches fixed with perforated plastic pipe which directed all leached liquid into plastic collection buckets. After about one month the leachate from 10 different sludges had from 1000-5000 mg/l total dissolved solids, 500-800 mg/l SO_4 and 150-600 mg/l Cl. Analysis for heavy metals showed less than 0.01 mg/l of nickel, zinc, iron, chromium and manganese. Only copper was present at 0.03-0.04 mg/l levels. Hardness (i.e. physical strength) is a function of the total amount of solids present and the quantity of reagents added.

g. Examples of past applications and current contracts: None reported.

a. Name of Vendor: Envirotech
3000 Sand Hill Road
Menlo Park, CA 94205

Contact: David L. Keaton, Vice-President

NOTE: For information on treatment of SO_2 sludges contact:
Walter Renburg, Jr.
Air Group/Pittsburgh
Envirotech Corporation
Two Airport Office Park
400 Rouser Road
Pittsburgh, PA 15108

b. Category of fixing process: The process is sodium silicate and cement-based. (U. S. Patent 3,837,872) Envirotech is the exclusive licensee in the field of fixed treatment units for National Environmental Control, Inc. (parent company of Chemfix Corporation).

c. Types of waste treated: Details available from company.

d. Types of waste excluded from treatment: Details available from company.

e. Approximate costs of processing: Figures available from company.

f. Data on leach and strength tests: Can be obtained from company.

g. Examples of past applications and current contracts: Contact company directly.

a. Name of Vendor: I. U. Conversion Systems, Inc.
115 Gibraltar Road
Horsham, PA 19044

Contact: Norman F. O'Leary, Vice President, Marketing; or
Richard W. Patton, Industrial Sales Manager
(215) 441-5920

b. Category of fixing process: The IUCS Poz-O-Tec process utilizes fly ash and other additives. The Poz-O-Tec chemistry is a combination of two simultaneous reactions: a rapid reaction that occurs between the soluble salts present in fly ash and the lime and alumina that is found in the fly ash glass; and a slower pozzolanic reaction that occurs between the silica in the fly ash and lime. the latter reaction occurs over a period of months.

c. Types of waste treated: This solidification system was developed initially for the electric utility industry for SO_2 scrubber sludge stabilization. Four million tons of FGC sludge is treated by this process in a single year.

Conversion Systems has also successfully stabilized and tested electroplating wastes, steel mill wastes, and chemical process wastes. Based upon these results, the process can stabilize or encapsulate wastes having the potential of leaching salts or heavy metals into the environment.

d. Wastes not suitable for treatment: Some organic wastes.

e. Approximate cost of fixation: Each waste must be evaluated for each client by Conversion Systems. Several alternative methods are available which result in somewhat different scopes of service. Preliminary cost estimates for processing sludges usually fall in the range of 1 to 7 cents per liter of waste. Some parameters influencing this range are quantity to be processed, water content, waste toxicity, equipment redundancy, desired methods of operation and scheduling requirements.

f. Leach and strength tests: Physical and environmental properties of Poz-O-Tec improve with time as the pozzolanic reactions proceed. The cementitious reaction produces a monolithic mass of low permeability which is subject to surface leaching only. The following is a compilation of typical structural properties of Poz-O-Tec stabilized material:

Wet density	1360-1600 kg/m^3 (85-100 lb/cu ft)
Dry density	1040-1360 kg/m^3 (65-85 lb/cu ft)
Moisture content	25-50% moisture
Cohesion	>95.7 x $10^3 N/m^2$ (>2000 lb/sq ft)
Unconfined compressive strength	>1.2 x $10^3 N/m^2$ (>25 lb/sq ft)
Permeability coefficient	10^{-6} to 10^{-8} cm/sec
Allowable bearing capacity	2.87 x $10^5 N/m^2$ (3 tons/sq ft)
Stable fill slope	2 horizontal to 1 vertical
Saturation	incomplete

Poz-O-Tec stabilized sludge may occupy more volume that the unstabilized sludge, but any increase in material is offset by the weight reduction brought about by dewatering the sludge before treatment and the greater heights to which the fixed sludge pile can be built in the disposal area.

g. Examples of past applications and current contracts: Conversion systems currently has contracted to fix 8 million metric tons of SO_2 scrubber sludge produced at eleven electric power plants in the U. S. It is also stabilizing all wastes from an SO_2 scrubber and water treatment plant of a large battery manufacturer.

The company is also developing alternative disposal applications where the physical characteristics of the fixed sludge can be used to advantage. Poz-O-Tec stabilized materials have been used as a base parking lot and road beds. Cast Poz-O-Tec blocks are currently under study for use in constructing artificial reefs.

Poz-O-Tec is a registered trademark of I. U. Conversion Systems, Inc.

a. Name of Vendor: Newport News Industrial Corp.
230 41st Street
Newport News, VA 23607

Contact: J. R. May, Manager, Radwaste Management Systems
(804) 380-7761

Newport News Industrial Corporation is primarily involved with volume reduction and waste handling techniques for radioactive materials. They have broad experience with producing compact wastes that are compatible with solidifying agents such as urea-formaldehyde, water extendable polyesters and bitumen. They are currently in the process of developing a new solidification method applicable to hazardous chemical wastes including radwastes.

b. Category of fixing process: Not available.

c. Type of waste treated: Not available.

d. Type of waste excluded from treatment: Not available.

e. Approximate cost of processing: Not available.

f. Data on leach and strength tests: Not available.

g. Examples of past application and current contracts: Process still in developmental stage.

a. Name of Vendor: Ontario Liquid Waste Disposal, Ltd. or
Canadian Waste Technology, Inc.
160 Torbay Road
Markham, Ontario L3R-1G6
Canada

Contact: David Krofchak, President, Canadian Waste Technology, Inc.
(416) 495-9502

b. Category of fixing process: The solidification process is based upon the production of stable silicate compounds analogous to natural geologic materials.

c. Type of waste treated: All inorganic wastes from heavy, medium and light industries such as waste pickle liquor, plating wastes, etc., containing acids, chromium, copper, iron, magnesium, manganese, nickel, zinc, cadmium, lead, mercury, vanadium, chlorides, sulphates, phosphorous and virtually any inorganic chemical or combination thereof. Specialized applications have been designed to treat mine tailing wastes and sewage sludges from primary and secondary treatment plants.

d. Types of waste excluded from treatment: The process is ineffective against some organic wastes, but organic wastes of up to 20% of the volume of the formulated inorganic wastes have been treated successfully on a case to case basis.

e. Approximate cost of processing: Each location where wastes are treated has different costs depending upon quantity of wastes and the method of operation. However, costs of approximately $8.00 per cubic meter ($6.00 per cubic yard) or 0.8 cents per liter (3 cents per gallon) are easily achieved (August 1977). This price assumes no cost for removal of solidified material from the site. No apparent increase in fixed material to raw sludge volume has been found.

f. Data on leach and strength tests: Extensive strength and leach tests have been made by the company; those cited below were in cooperation with the Ontario, Canada, Ministry of the Environment, Pollution Control Branch, Industrial Section (from a paper entitled "An Assessment of a Process for the Solidification and Stabilization of Liquid Industrial Wastes, 1976, by G. A. Kerr, Q.C., Minister) the conclusions of this report were:

(1) The solidification process appeared to hold and stabilize most of the heavy metals contained in the liquid (acidic metal-bearing liquid industrial wastes). Heavy metal values in the leachates (laboratory and field) were commonly below 1 mg/liter.

(2) Leachates from the testing of processed material contained high concentrations of dissolved solids.

(3) The bulk of the common heavy metals present in the waste were retained in the processed material during extended period of leaching with

distilled water when considered on a mass basis. Losses of heavy metals were relatively minor.

(4) Landfilling may be used to dispose of the processed material providing adequate facilities are available for the collection and treatment of leachate and run-off. The concern over dissolved solids contamination will dictate the adequacy fo the facilities required.

Material with up to 20.7×10^6 N/m^2 (3000 psi) unconfined compressive strength has been produced, but for reasons of cost, the end product is generally of low strength.

g. Examples of past applications and current contracts; Currently over 380,000 liters/day (100,000 gpd) are being treated at a treatment site in the city of Hamilton, Ontario. The fixed material is being used as a cover for the sanitary landfill. Negotiations are currently underway with companies in the United States and in Canada for the licensing of the technology to operate similar sites and many cases to treat company wastes on site.

a. Name of Vendor: Polymeric Materials Section
Department of Materials Science and Engineering
Washington State University
Pullman, WA 99164

Contact: R. V. Subramanian
(509) 335-6784

NOTE: The Department of Materials Science and Engineering, Polymeric Materials Section is not a vendor of the raw materials and equipment necessary for fixation, but has extensive experience and developmental expertise in the polyester encapsulation of hazardous wastes. In cooperation with members of the Department of Chemical Engineering, this technology has successfully been developed through the pilot plant stage.

b. Category of fixing process: An organic polymer (polyester resin) is used to solidify the wastes.

c. Types of waste treated: Although very broadly effective, the process appears to be quite effective for low-level radioactive wastes, metal ion wastes, cyanides, arsenic wastes, and some specific organic wastes such as kepone, PCB, and some pharmaceuticals.

d. Type of waste excluded from treatment: The process is not effective on very highly acidic sludges (especially at pH less than 1.0).

e. Approximate cost of processing: The price of polyester resin is about $1.00/kg (45 cents/lb). Since the maximum volume fraction of close-packed spheres is 74%, the minimum amount of resin which must be added to the waste is about 25% by volume. The fixed waste is usually 133% to 175% of the volume of the unfixed waste.

f. Data on leach and strength tests: Tests made using a fixed product encapsulating 60% by weight of a 24% sodium sulfate solution indicated compressive strength of 15.0×10^6 N/m^2 (2180 psi). Irradiation with 600 Mrad gamma radiation actually increased the compressive strength to 20.7×10^6 N/m^2 (3000 psi). The strength of the product is dependent upon the type, proportion and form of waste incorporated.

The leachabilities of Co-58, Sr-85, and Cs-134 from a similar encapsulated sodium sulfate waste were 3.2×10^{-3}, 3.5×10^{-3}, and 5.9×10^{-3} cm, respectively over a period of 120 days. The leach curves leveled off at this value after an initial rise in the first 20 days. Thus, the leachability, after the initial dissolution of surface material, was practically negligible.

g. Examples of past applications and current contracts: Ontario Hydro, Toronto, Ontario is pursuing this process for radwaste encapsulation.

a. Name of Vendor: Protective Packaging, Inc. (NECO)
A subsidiary of Teledyne Corp.
328 Production Court
Jeffersontown, KY 40299

Contact: Charles Jay
(502) 491-8300

b. Category of fixing process: The company sells an organic polymer solidification system.

c. Types of waste treated: Company has extensive experience with nuclear wastes, both in solidification and disposal. Details are available from the company.

d. Types of waste excluded from treatment: Consult company directly.

e. Cost of fixation: Information available from company.

f. Leach and strength test: Details on testing with radwastes available.

g. Examples of past applications and current contracts: Available directly from company.

a. Name of Vendor: Sandia Laboratories
Albuquerque, NM 87115

Contact: R. L. Schwoebel, Manager
Chemistry and Materials Characterization Department
(505) 264-4309, ext. 5820

NOTE: Sandia's waste management program is wholly oriented toward stabilization of radiation containing wastes (July 1975).

b. Category of fixing process: The Sandia Solidification Process project is a feasibility study of the solidification of solid wastes. Fission product cations and actinides undergo ion exchange on inorganic ion exchangers being developed at Sandia Laboratories. These ion exchangers are hydrous oxides of Ti, Zr, Nb, Ta.

c. Type of waste treated: The process is designed for high-level radioactive wastes such as the high level waste stream resulting from commercial nuclear fuel reprocessing was well as caustic defense waste streams with high salt ($NaNO_3$) contents.

d. Type of waste excluded from treatment: The high cost of process precludes low value, low hazard wastes.

e. Approximate cost of processing: Cost estimates for continuous column flow systems are comparable to glassification processes. Periodic batch processing would probably be cheaper than glassification.

f. Data on leach and strength tests: The final product, subsequent to ion exchange, could be fired to produce a ceramic product (mixed titanates and titania) having leach rates as much as an order of magnitude lower than that of borosilicate glass stabilized waste.

g. Examples of past applications and current contracts: Process in feasibility study stage only.

a. Name of Vendor: Sludge Fixation Technology, Inc.
227 Thorn Avenue
P. O. Box 32
Orchard Park, NY 14127

Contact: Richard E. Valiga
(716) 662-1005

b. Category of fixing process: The Terra•Crete process is a "self-cementing process" based on the production of a cementitious material from calcium sulfite hemihydrate or calcium sulfate. A portion of the sulfite/sulfate sludge stream is dried and calcined to produce a cementitious agent. This material and other additives (as needed) are introduced into the waste stream and react to form a hard, low permeability mass from the sludge.

c. Types of waste treated: The system is primarily designed to operate with sulfite/sulfate-based sludges produced from SO_2 stack scrubbing operations but is adaptable to other situations where calcium sulfite/sulfate sludges can be obtained.

d. Types of wastes excluded from treatment: Not specified.

e. Cost of fixation: A flue gas cleaning sludge would cost between $2.00 - 2.75 per ton for fixation.

f. Leach and strength tests: Data on leaching of antimony and lead-rich flue gas cleaning sludge shows <0.01 ppm lead in the leach liquid. The unconfined compressive strength obtained from the Terra•Crete material depends on the amounts of additive used, but data showing strengths from 9.57×10^4 N/m^2 (200 lbs/ft^2) to 5.74×10^5 N/m^2 (12,000 lbs/ft^2) are available. Permeabilities are on the order of 10^{-6} to 10^{-7} cm/sec.

g. Examples of past applications and current contacts: None specified.

Terra•Crete is a registered trademark of Sludge Fixation Technology, Inc.

a. Name of Vendor: Southwest Research Institute
8500 Culebra Road
P. O. Drawer 28510
San Antonio, Texas 78284

Contact: John M. Dole, Manager
Process Research & Engineering

NOTE: Southwest Research Institute (SRI) is a cntract research organization and as such is not marketing processes or products.

b. Category of fixation process: Two fixation processes have been developed:

(1) SRI has developed a thermoplastic epoxy system that combines the better features of thermosetting epoxy system with the better features of thermoplastic systems. Low-cost extended epoxy resins and hardeners which are solids at ambient temperatures are heated (204°C) where they become low viscosity liquids. They are then combined and mixed with heated fillers or aggregates and discharged. They set instantly as thermoplastic materials and then cure as a thermosetting material to provide the typical physical property features of epoxy containers. These epoxy materials can be used as coatings for other fixation processes.

(2) Three different systems using sulfur have been developed for industrial sludge stabilization. These systems are: (a) a modified sulfur process where sulfur is used as a binder for the toxic sludge to produce a concrete-like material. Since sulfur melts at about 120°C, the sludge must be heated and dried before processing. Because of the brittle nature of sulfur, a modified form is usually found to be superior for concrete applications; (b) the plasticized liquid sulfur system is a new development in which sulfur is modified to the extent that is can be used as a substitute for asphalt; (c) the third process is sulfur impregnation. Sulfur has been used previously as an impregnation agent for concrete, gypsum, porous brick, tile and mud block. In addition to filling the voids to reduce water absorption, considerable strength improvements also result. This system is of use in increasing the strength and leach resistance of sludge fixed by other methods such as concrete admixing. Most of the sulfur composite work listed above is still in the developmental stage.

c. Types of wastes treated: Not fully determined.

d. Wastes not suitable for treatment: Not fully determined.

e. Approximate cost of fixation: Not determined.

f. Leach and strength tests: Not yet available.

f. Examples of past applications and current contracts: Currently in development and testing phase.

a. Name of Vendor: Stabatrol Corporation
1402 Conshohocken Road
Norristown, PA 19401

Contact: Richard E. Valiga
(215) 279-3992

b. Category of fixing process: The Terra•Tite process involves the addition of cementitious materials to the waste sludge to produce a concrete-like material.

c. Types of waste treated: Most industrial wastes can be treated. The Terra•Tite process has great technical flexibility.

d. Types of wastes excluded from treatment: None specified.

e. Cost fixation: None specified.

f. Leach and strength tests: Permeabilities on the order of 10^{-7} cm/sec are obtained. Leaching is insignificantly low. Terra•Tite material has shown unconfined compressive strengths up to 4.78×10^5 N/m^2 (5 tons/sq ft).

g. Examples of past applications and current contacts: Heavy metal sludges, 50,000 tons; heavy metal salt cake, 10,000 tons; contaminated soils, 5,000 tons.

Terra•Tite is a trademark of Stabatrol Corporation.

a. Name of Vendor: Stablex Corporation
Suite 112
2 Radnor Corporation Center
Radnor, PA 19087

Contact: John Scofield
(215) 688-3131

b. Category of fixing process: The patented technology, described as Sealosafe, involves adding two silicate-based powders to the waste which is dissolved or dispersed in water thereby producing a slurry and the slurry sets into a rigid, rock-like cast. Due to its physical and chemical form, this mass is referred to as synthetic rock.

The physical and chemical interactions which take place simultaneously are referred to as the mechanism of crystal capture. Up to ten additional ingredients are also used, depending upon the type of waste to be treated, to enable the cyrstal capture mechanism to operate under optimum conditions.

c. Types of wastes treated: The process is suitable for:

(1) All inorganic wastes.

(2) Organic wastes which can be homogenously incorporated into an aqueous phase either by dissolution, suspension, or absorption.

(3) Wastes in (1) or (2) above in liquid, solid, or sludge form, including contaminated articles such as filter cartridges, clothing, rubber boots, etc.

(4) The process is exceptionally successful in treating all heavy metals, arsenic, mercury and asbestos. The process also deals with anionic wastes such as fluoride, chloride, etc.

d. Wastes not suitable for treatment: The process is not suitable for solidification of:

(1) Oils, solvents, and greases which are not miscible with an aqueous phase.

(2) Very large quantities of water with minimal amounts of toxic ingredients.

e. Approximate cost of fixation: In typical applications one ton of waste would yield 1.15 to 1.4 tons of end product, called Stablex. The volume increase in this weight increase is between 5% and 10%.

Precise cost estimates were not possible because of the different properties of the wastes to be treated. Experience indicates an extremely broad range of between $5.00 to $350.00 per ton depending upon the type, quantity and complexity of the waste involved.

f. Leach and strength tests: Extensive experience and information is provided by the company. The product, Stablex, is 10 times less permeable than concrete. Leaching tests in which fixed samples are ground to a fine powder and totally immersed and wetted in ten-times their weight of distilled water for one hour indicate that very little material is lost to the water. One example using a solid waste fixed by the process and hardened for three days (and containing 39,000 ppm copper, 46,000 ppm zinc, and 42,000 ppm chromium) lost less than one ppm of these toxicants. The product, Stablex, has an unconfined compressive strength about equal to that of the grouts used for void filling and soil stabilization but much lower than concretes and mortars.

g. Examples of past applications and current contracts: A treatment center near Birmingham in the United Kingdom has a current throughput of 200,000 tons of waste per year (its capacity was increased from 70,000 tons per year in 1978). Another treatment center near London, U. K., was commissioned in 1978 with a capacity of 400,000 tons per year. Both plants operate as regional treatment plants handling a variety of wastes from different sources. Construction of two plants in Japan and the first plant in the U. S. has been scheduled to begin in 1979.

The Sealosafe Service includes a process protected by patents and patent applications in the United States and overseas and Sealosafe and Stablex are trademarks of the Stablex Group of Companies.

a. Name of Vendor: TJK, Inc.
7407 Fulton Avenue
North Hollywood, CA 91605

Contact: Masaaki Endo, General Manager
(213) 875-0410

NOTE: This company has contracted to market the Takenaka Sludge Treatment (TST) System (Takenaka Komuten Co., Osaka, Japan) in the U. S. Studies conducted by EPA on Kepone and arsenic disposal problems are now underway.

b. Category of fixing process: Hardeners are principally cement-family or cement-based materials. In addition, special additives are used for stabilizing harmful substances. Several series of hardeners are used depending upon the specific mud or sludge to be treated.

c. Type of waste treated: The TST system is a technique for solidifying mud of comparatively high water content or sludge discharged from factories and plants. It transforms the material into a form easy to handle for utilization in land reclamation and pollutant control. Treatable material can be widely dispersed, settled sludge or sludge obtained directly from the factory or plant. In the case of sludges with toxic substances such as mercury, chromium and cadmium, TST treatment stabilizes and chemically fixes these harmful substances.

d. Types of waste excluded from treatment: Two types of sludges tested but found unsuitable are sludge produced from a wool scouring plant (greater than 20% fats and oils) and sludges containing large amounts of paint wastes.

e. Approximate cost of processing: Costs of processing will, of course, vary with the type of sludge and additives required but will run from about $\$10/m^3$ ($\$8/yd^3$) to $\$20/m^3$ ($\$16/yd^3$). These estimates do not include transportation or disposal. Volume increase upon treatment is from 1.05 to 1.15 times pretreatment volume.

f. Data on leach and strength tests: Extensive leach testing has been carried out by the company. In their standard leach test, the treated sludge is ground to a particle size between 0.5 mm and 5 mm. This powder is then mixed with distilled water and adjusted to pH of between 5.8 and 6.3 with HCl or CO_2. The final mixture (100 ml) is 10% (weight/volume) sludge to water. This mixture is stirred for 6 hours at room temperature and 1 atmosphere and then filtered or centrifuged before analysis. Results of tests made with a wide variety of sludges and muds containing a wide variety of toxic metal ions show that only low levels of pollutants are released even in the relatively severe leaching test. (Ions reported and their maximum allowable concentrations: Alkyl-Hg and Hg, no detectable; Cd, 0.3 mg/ℓ; Pb, 3 mg/ℓ; organic-P, 1 mg/ℓ; Cr^{-6}, 1.5 mg/ℓ; As, 1.5 mg/ℓ and CN, 1 mg/ℓ.)

Unconfined compressive strength varies widely with the type of sludge and kind and amount of additives used, but values of 5-10 x 10^5 N/m^2 are not unusual with 20% (w/v) additives.

g. Examples of past applications and current contracts: Twenty-six projects have been completed since 1973. Seventeen projects involved deposits under water (46,000 m^3), seven involved factory discharges (14,500 m^3). In the majority of these projects toxic substances were successfully contained.

a. Name of Vendor: Todd Shipyards Corporation
Research and Technical Division
P. O. Box 1600
Galveston, Texas 77553

Contact: C. E. Winters, Jr., Sales/Marketing Representative
(800) 231-2868/2869 (713) 744-7141

b. Category of fixing process: The organic polymer product called "Safe-T-Set", is a non-toxic, non-hazardous, powdered, thixotropic thickner which is effective with concentrated wastes as well as liquids. Safe-T-Set solidifies into a homogenous mix with no liquid displacement. It is not a urea-formaldehyde formulation.

c. Types of waste treated: This product was designed specifically for industrial radioactive waste sludges. Tests have not been made with general industrial wastes at this time (Dec 1978).

d. Type of waste excluded from treatment: No extensive tests have been made.

e. Approximate cost of processing: Costs will vary with the amount of additive used to solidify the mass. Typical data given by the company indicate that 6 to 20% Safe-T-Set are typical and give hardening time of 14 to 3 minutes respectively at 21°C. The cost of Safe-T-Set is approximately $6.60/kg in 500 kg quantities (4/77). Additive costs (at 10%) would be approximately $600 per ton of fixed waste.

f. Data on leach and strength tests supplied by the company: Extensive leaching and strength tests are reported by the company. These tests were conducted with simulated radioactive wastes and were designed to prove that Safe-T-Set, when mixed with radioactive liquid waste, would minimize activity release if container integrity was lost during transportation or after disposal by burial. Nine tests were performed: Escape of radioactive material through Safe-T-Set and soil, temperature cycle tests, immersion study of pH dependance, pH of fixation, immersion study at pH 7.0, off gas study, stability when innoculated with bacteria, irradiation and toxicity.

g. Examples of past applications and current contracts: No information available.

Safe-T-Set is a trademark of Todd Shipyards Corp.

a. Name of Vendor: TRW Systems Group
One Space Park
Redondo Beach, CA 90278

Contact: H. R. Lubowitz, Staff Scientist
(213) 535-4321

NOTE: TRW Company has done extensive testing, development and evaluation on fixation technology for the EPA. Data below was taken from Recommended Methods of Reduction, Neutralization Recovery or Disposal of Hazardous Waste by Burk, Derham, and Lubowitz or TRW, USEPA contract #68-03-0089, 21 June 1974, and Lubowitz and others, 1977, Development of a Polymeric Cementing and Encapsulating Process for Managing Hazardous Wastes, EPA-600/2-77-045.

b. Category of fixing process: The two types of fixation additives which were selected for best overall potential and then studied and tested extensively were:

(1) Inorganic cements: Type 2 Portland cement, plaster of paris (calcium sulfate hemihydrate) and lime (pure calcium oxide).

(2) Polybutadiene resins of specific stereo configurations (atactic 1, 2 polybutadiene).

All fixation techniques were tested with and without jackets of both thermoplastic and thermosetting resins and asphalt.

c. Types of waste treated: All types of solid wastes and sludges were felt to be treatable, but the specific wastes treated in this study were simulated solid wastes and sludges containing compounds of six toxic elements: arsenic, mercury, selenium, chromium, cadmium, and lead.

d. Wastes not suitable for treatment: None given.

e. Approximate cost or processing: Process design and economics were covered extensively in the study. Details of the design and economics of both the organic and inorganic encapsulation processes, cost benefit analysis and a summary of results were included. Raw material cost was the factor most affecting the process costs and was a primary consideration in the original selection of the fixation processes.

f. Data on leach and strength tests: Extensive tests were made and results are available. Tests made included: mechanical testing, determination of bulk density, surface hardness, and compressive strength; microscopic examination of the interface between fixed specimen and the coating and leaching experiments using three leaching solutions (distilled water, saturated carbonic acid of pH 3.8 to 4.0, and 0.1M sodium sesquicarbonate solution). Leaching was conducted at room temperature in 750 ml of leaching solution which was mildly agitated twice per day.

g. Examples of past applications and current contracts: Not available.

a. Name of Vendor: Werner and Pfleiderer Corp.
160 Hopper Ave.
Waldwick, NJ 07463

Contact: John Stewart or Richard Doyle
(201) 652-8600

NOTE: Werner and Pfleiderer Corporation manufactures equipment for incorporating low and intermediate level radwastes into a bitumen or plastic matrix. Their equipment and their techniques have been used in almost all testing of bitumen encapsulation of hazardous industrial wastes.

b. Category of fixing process: The technique used is bitumen encapsulation or incorporation using a screw extruder.

c. Types of wastes treated: No industrial wastes are currently being stabilized by asphalt encapsulation but, testing of asphalt encapsulated arsenical wastes has been undertaken by the U. S. Environmental Protection Agency.

d. Types of wastes excluded from treatment: Sludges containing strong oxidizers such as nitrates, chlorates, perchlorates and persulfates should not be encapsulated in asphalt. Sludge containing borates may require special handling because they tend to cause early hardening of asphalt materials. Salts that swell excessively on rehydration may require special processing.

e. Cost: Not available for industrial wastes at this time. Usually wastes are mixed on 1-to-1 weight ratio asphalt to dry wastes. Asphalt of suitable grade for blending costs 13 to 35 cents per kg. Capital, operating expenses are presently not available for non-radioactive disposal operations. The cost of secondary containers (55-gallon steel drums) must also be added in.

f. Leach and strength tests: According to information furnished by the company, leach rates 100 times less than those observed with comparable cement mix can be expected. If the microdispersed salt/asphalt mix is coated with as little as 5 mm (0.2 in.) of pure asphalt the leach rate was zero in distilled water over a period of two and one-half years. Strength test data is not obtained for asphaltic mixes as they are plastic solids that are usually placed in steel containers.

g. Examples of past applications and current contracts: Full scale radwaste encapsulation units are in operation at Marcoule, France and Karlsruhe, West Germany. No one is presently using similar equipment in industrial waste processing.